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Studies on MOSFET Low-Frequency Noise for Electrometer Applications

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1. Introduction

In a previous study [1], we examined the possibility of using a submicron SOI MOSFET fabricated by the foundry process as a sensitive electrometer. Although the device is not the latest in terms of dimensions, it actually has the ability to detect single electrons at 8 K. The purpose of the present work is to assess the sensitivity of the MOSFET with consideration of noise.

Here, we report detailed low-frequency noise measurements in n-channel SOI MOSFET, performed under various bias conditions ranging from subthreshold to linear regime at 8 K. To evaluate the effect of the channel dopant, undoped devices are characterized along with conventionally doped devices.

2. DC characteristics and different operating regimes

MOSFETs were fabricated using a 0.15-μm fully depleted SOI CMOS process. Gate length L and width W are 0.14 and 0.32 μm, and gate oxide thickness t_{ox}, silicon film thickness t_{soi} and buried gate oxide thickness t_{box} are 5, 40 and 200 nm, respectively. The channel boron concentration is 5×10^{17} cm^{-3} in conventional and less than 10^{15} cm^{-3} in undoped devices. Drain current I_D is plotted against the gate voltage V_G for different back-gate voltages V_{BG} at T=8 K in Fig. 1(a) (conventional) and Fig. 1(b) (undoped). The drain voltage V_D is 50 mV. From these curves, we obtain the graph of V_G-V_{BG}, where I_D=10 nA [Fig. 1(c)]. This allows us to identify the different operating regimes depending on the doping level and (V_G,V_{BG}). All curves tend to follow the same asymptotes when V_{BG}<<0 (front-channel) and V_{BG}>>0 (back-channel). At 8 K, an intermediate zone appears with a gentle slope, corresponding to the depletion of the substrate [2]. Circles indicate the biasing conditions selected for noise measurement.

3. Noise in conventional MOSFET

The drain current power spectrum noise S_I in the conventional MOSFET at 8 K for different channel resistances R is shown in Fig. 2. In the frequency range (0.1 Hz – 100 kHz), we observe a Lorentzian spectrum with a cut-off frequency fc at around 200 Hz. This spectrum is linked with the Random Telegraph Signal (RTS) noise in the time domain [Fig. 2(b)]. A reasonable fit of the spectrum is obtained from the RTS data and the equation

$$S_I(f) = \frac{N\left(4\delta I_D{}^2\right)}{(\tau c + \tau e)\left[\left(\frac{1}{\tau e}+\frac{1}{\tau c}\right)^2 + (2\pi f)^2\right]}, \qquad (1)$$

where δI_D is the step height in the RTS current noise, and τc, τe are the average capture and emission time of the traps. Equation (1) considers the noise signal as a sum of N independent two-level signals [3] of similar time constant and δI_D. The extracted parameters for this particular signal are N=3, $\delta I_D = 8.5 \times 10^{-10}$ A, τc=1.7 ms, τe=1.5 ms, $S_I(f<fc) = 4.3 \times 10^{-22}$ A^2/Hz, and fc=200 Hz.

In the previous study on the charge sensitivity of the MOSFET [1], we obtained current step caused by the input of an electronic charge ΔI_D=0.04 nA/electron at R=300 MΩ. Combining this and the noise spectrum in Fig. 2(b), the charge noise spectral density at 10 Hz is calculated to be

$$Sq^{1/2} = S_I{}^{1/2}/\Delta I_D = 0.025 \text{ e/Hz}^{1/2} \qquad (2)$$

4. Noise in undoped MOSFET

RTS noises in the conventional MOSFET are obviously an obstacle when we intend to detect single electrons. We found that the RTS noise and the Lorentzian noise are greatly reduced by the use of the undoped MOSFET. For this, the drain current power spectrum noises S_I at 8 K for different channel resistances are shown in Fig. 3(b) (V_{BG}=-6 V). The spectrum is mostly 1/f-like and the noise levels are generally smaller. The charge noise spectral density at 10 Hz (Fig. 3, R=300 MΩ) is

$$Sq^{1/2} = 7.8 \times 10^{-3} \text{ e/Hz}^{1/2} \qquad (3)$$

This value is more than three times smaller than that for the conventionally doped MOSFETs and the GaAs FET in the literature [4]. Although it is still three orders of magnitude higher than the SET electrometer, the record [5] being 8×10^{-6} e/Hz$^{1/2}$, we could improve the performance by reducing the channel resistance, as will be discussed below.

5. Discussion

The difference between doped an undoped MOSFETs highlight the possibility that dopants contribute to the noise at low temperature. At 8 K, dopants are not all ionized in the silicon film, depending on the gate voltage. For this reason, a generation/recombination noise may occur. In addition, at low temperature, potential fluctuation caused by the dopant charges plays a major role in the electronical transport because of the Coulomb blockade [6], which is manifested by the current fluctuation in Fig. 1(a) and its temperature and drain voltage dependences (data not shown).

Though the level of the charge noise is rather large, there is room for improvement. The estimated value was obtained at R=300 MΩ, in the subthreshold region. However, in this regime, $\Delta I_D/I_D$ is constant, and $Sq^{1/2} \propto S_I{}^{1/2}/I_D$ slightly decreases with the channel resistance (at a given frequency). Therefore, Sq could be further reduced at lower channel resistance.

In the linear regime, the charge sensitivity is constant, whereas the noise increases with the current. The optimum biasing point for a small Sq should be at the boundary between the subthreshold and linear regimes.

5. Conclusion

The low-frequency noise of submicron SOI MOSFETs has been studied for electrometer applications. We found that the devices without channel dopant exhibit smaller noises at 8 K, and that they attain the charge noise spectral density of 7.8×10^{-3} e/Hz$^{1/2}$ at 10 Hz, which is more than three times smaller than that of the GaAs FET in the literature. Since the devices can be easily fabricated by the foundry process, the results open up the possibility of ultra-sensitive electrometer integrated with electron-transfer-type devices and circuits.

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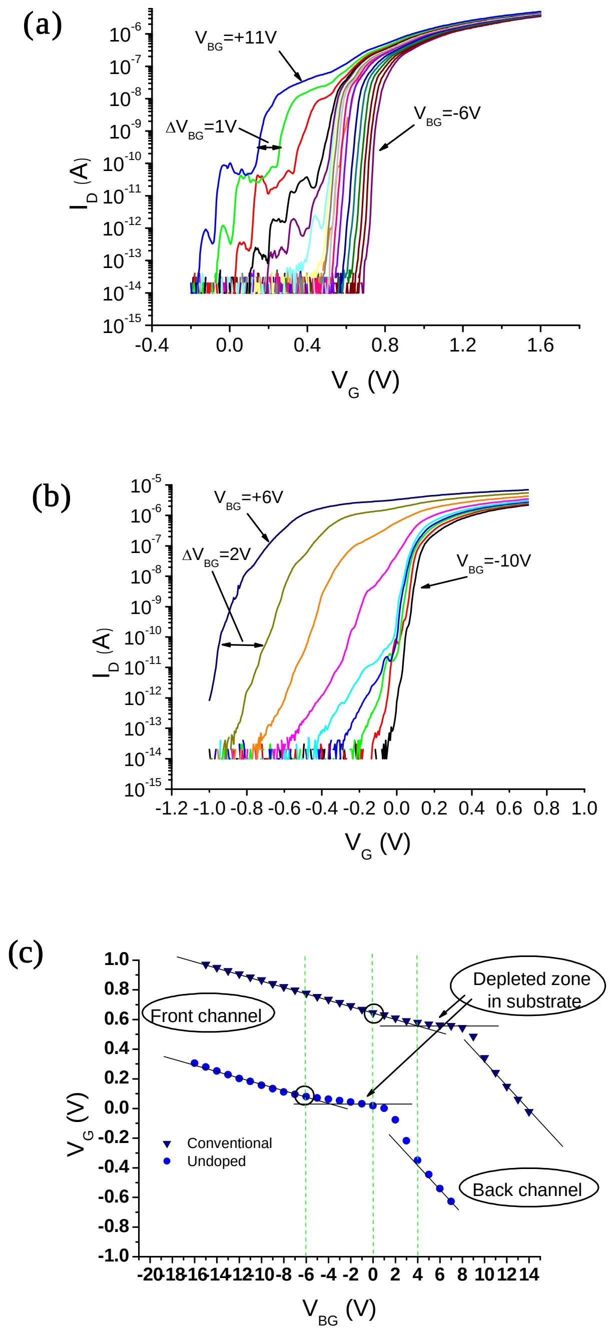

Fig. 1. I_D-V_{GS} characteristics of SOI MOSFETs (L=0.14 μm, W=0.32 μm, tox=5 nm) at V_D=50 mV, T=8 K for conventional (a) and undoped (b) SOI. (c) V_G-V_{BG} at I_D=10 nA for conventional and undoped SOI.

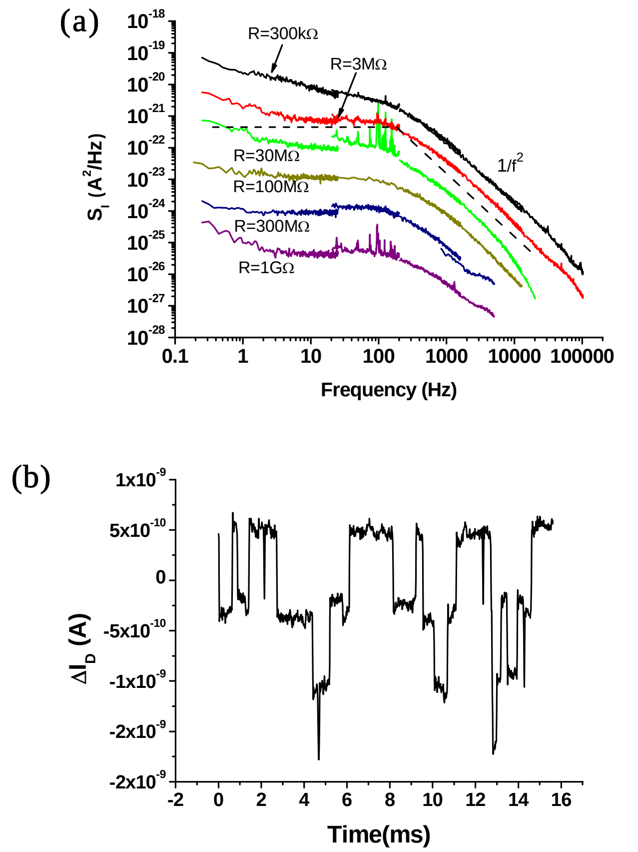

Fig. 2. (a) Power spectrum noise S_I for different channel resistances R at 8 K for conventional SOI. V_D=50 mV. (b) RTS noise at R=3 MΩ.

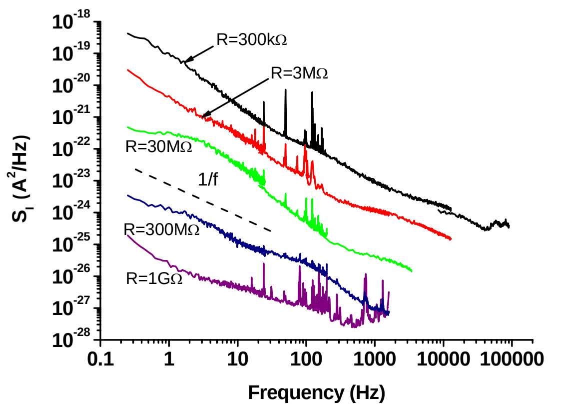

Fig. 3. Power spectrum noise S_I for different channel resistances R at 8 K for undoped SOI with V_{BG}=-6 V.